

Modelling Information Age Warfare: Work In Progress

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*‘An opportunity to grow rich crops on this fertile but largely unploughed ground’.
(Hughes W P (1997). *Military Modelling for Decision Making*, 3rd Edition. Military
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Abstract

The uncertainties of future scenarios require us to carefully investigate the real problems and issues to be addressed in modelling and analysis of Command and Control. This problem formulation process then needs to be supported by new tools for problem solution. In consequence, a new generation of Command and Control centred constructive simulation models of conflict is being developed by Dstl in the UK. These have a coherent approach to the representation of Command and Control which is described in the paper. This baseline approach is then complemented by mathematical models of such processes (‘metamodels’) which give insight into the likely modes of emergent behaviour.

Introduction

A major pressure acting on defence operational research studies is the need to address a wider span of likely futures (*scenarios*) in studies, reflecting increased uncertainty in the post-Cold War world. Another reflection of this uncertainty is the need to consider a wide range of sensitivity analysis, and to do this quickly enough to influence the decision process. In this paper we discuss the consequences of this in terms of the need firstly to carefully structure and formulate the problem before going on to problem solution. The implications for such problem solution are then considered in terms of agile constructive simulation models, complemented by mathematical ‘metamodels’ of the system of concern.

Problem Formulation

The uncertainty inherent in likely futures implies that the real problem is likely to be ill defined and obscure, especially if it involves Command and Control issues. Any good analysis must thus start by trying to define what the real problem is, before going on to the problem solution – An approximate analysis of the real problem is worth more than a detailed analysis of the wrong problem.

In simple terms, such problem formulation can thus be seen as an iterative process. First, the study team must identify the variables that bound the problem space. Then they must determine which of these are outputs (dependent variables) and which of these are inputs (independent variables). The team then proceeds by iterating to build

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an understanding of how these relate to each other. It should be viewed as a voyage of discovery. In most, if not all cases of C2 assessment, the knowledge domain under study is in fact a system characterised by rich interaction and feedback among all the factors or variables of interest. The choice of dependent variables results from a clear specification of the issues and products needed to satisfy the terms of reference. Independent and intervening variables are also chosen based on the purpose of the analysis. More detailed guidance on how to carry out this problem formulation process is given in the new version of the NATO Code of Best Practice for Command and Control Assessment, to be issued shortly.

Having formulated the problem, we then need to solve it. In this process, the tools we use have to support faster turnaround of analysis, while at the same time covering a larger spread of scenarios and sensitivity analysis. In the context of constructive simulation modelling (the method of choice for a large proportion of our problems), this points to the need for models, incorporating the effects of C2¹, which run at rates very much faster than real time, and which are easily transportable across different situations and scenarios (we call these *agile* models).

A new generation of such constructive simulation models is being constructed at Dstl in the UK, with C2 at their heart. These models span the range from Joint Campaign level warfighting, to Peace Support operations. We firstly lay out the essential ideas behind this C2 representation.

Alternative Command Structures

In Reference 1, a number of differing command arrangements are described which span the major approaches to the C2 of armed forces. From the discussion in Reference 1, it is clear that varying command structures can be captured by a combination of top down and bottom up approaches, as shown in Figure 1.

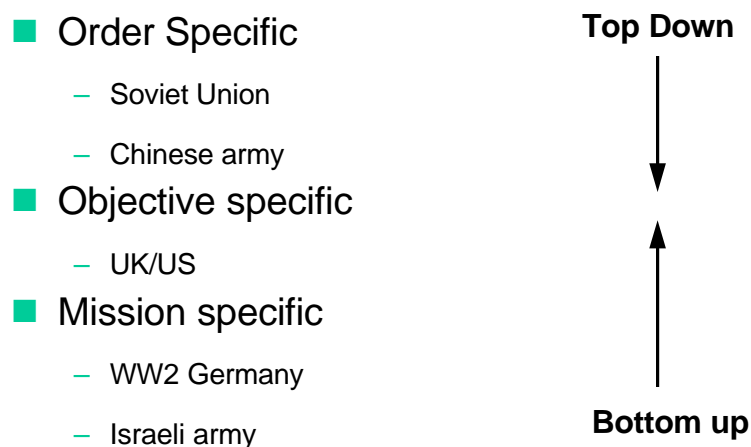


Figure 1: Alternative Command Structures.

¹ The term Command and Control (C2) is taken to cover all the activities associated with sensing, situation assessment, decision making, communication, and all other aspects of command and control.

‘Order Specific’ corresponds to a very top-down oriented command structure. This is relaxed at the next level, where specific objectives are decided by the higher command, but subordinate local forces have some initiative in terms of how to achieve the objective. ‘Mission specific’ refers to an even more open command structure in which local commanders have full autonomy to ‘self-synchronise’ with other local commanders in order to achieve broad mission goals (comprising a number of objectives necessary to accomplish the mission), with little interference from higher command. Recent UK doctrine has moved more to the bottom end of this spectrum, as ‘mission command’

One of the central issues behind the provision of C2 capability is thus the balancing of centralised and decentralised control - of local autonomy with top down authority. The C2 organisational structure also depends on the ratio between ‘C2 speed’ and ‘battle speed’: if the battle speed increases beyond a certain point, then C2 reverts to local organisation (that is, the system becomes self-organising). A similar point is made in current UK army doctrine concerning command²: ‘The more fluid the circumstances, the lower the decision level should be set’. Thus any representation of the C2 process must be able to represent the interaction between these top down and bottom up effects. We use this approach as a basis for representing the C2 process as a combination of both top down (‘Deliberate Planning’) and bottom up (‘Rapid Planning’) processes.

Rapid Planning

As the operational dynamic becomes more fluid (i.e. the ratio of battle speed to C2 speed increases) the system tends to move towards self-organised local command. Lack of time at the tactical level due to the increase in this ratio of battle to C2 speed leads to an increase in more ‘intuitive’ approaches to decision-making³. These approaches conform to Klein’s Recognition Primed Decision -Making (RPDM) model of the decision-making process⁴, applicable to expert decision-makers under stress.

Pattern Matching

In order to capture the essence of the RPDM approach, the Rapid Planning process thus uses a form of pattern matching, where the patterns are directly linked to possible courses of action. This is achieved by exploiting the mathematical properties of the Dynamic Linear Model (DLM), as discussed in detail in Reference 5.

In analysing the commander’s approach to Rapid Planning, we consider first the idea of an ‘OK’ and ‘not-OK’ situation. Commanders have a general sense of how things are going. They take the information they have and weave it into a plausible story (the OK state). At this level, what is required is a method of assessing when the commander is approaching the boundaries of the OK state. When the perception is that the pattern of events has significantly changed, he crosses the boundary of the OK state and has to decide whether to remain with his current mission, or change to a new mission. Corresponding to the spirit of mission command, (the lowest of the three levels of C2 structure discussed earlier) it is assumed that there is a small set of alternative missions defined (such as advance, attack, defend, delay, withdraw, or alternatives in other domains such as maritime warfare or peacekeeping). These

missions are applicable to any level of command, so that the process is recursive. Thus the Rapid Planning problem is the same at every command level; namely whether to move from one of these missions to another, at any given point in time.

The 'perceived pattern of events' will in general be defined by a number of attributes. These factors define a configuration space, which we call the Recognised Picture. The approach to Rapid Planning is thus as follows:

- Quantify the current values of the factors which constitute the Recognised Picture (RP).
- Determine whether the RP has changed significantly. If not, then the situation is OK, and no mission change is required.
- If the story no longer holds together, i.e. the situation is changing significantly and we are moving into the not-OK situation, compare the pattern corresponding to the recognised picture with a set of fixed patterns which represent the commander's stored understanding. These fixed patterns correspond to particular regions of configuration space.
- Find the best match.
- Test the course of action associated with this pattern for feasibility.
- If feasible, implement mission change.

Deliberate Planning

We also wish to capture within such intelligent agent models, the likely broad courses of action at the campaign level. It is necessary (of course) to include in the model the fact that perception of the other side's intent (this is, his broad course or courses of action) is imperfect, and is a function of intelligence and sensor information. At this level, each of these alternative courses of action can be described by a route (on land or water) through a number of zones. Each of these zones represents a significant piece of terrain (such as an area of ground of a particular type, or a volume of sea of constant sonar conditions). For each of the two sides, each of the enemy intents (i.e. enemy Courses of Action) is assigned a prior probability, and these are updated using a Bayesian approach as information from sensors looking at the various zones is updated. Denoting the two sides as Blue and Red, Blue's problem is to define a general layout of his forces, taking account of the probabilities of the different perceived Red intents. Red also has the same problem in relation to Blue, and the structure of this process is akin to a hypergame, where each side in a two-person game has a separate payoff matrix based on perceptions. Given an allocation of forces by both sides, the first problem is how to assess the effectiveness of such an allocation. This is done through the use of historical analysis. Such historical analysis employs non-linear multivariate regression to relate measures of merit for a high level plan (e.g. the probability of breakthrough) to the underlying force allocation assumptions.

Genetic Algorithms

The use of Historical Analysis in this way allows a complete Campaign Plan to be very rapidly evaluated in terms of high level measures of force effectiveness (MoFE)

The use of Genetic Algorithms to ‘breed’ a number of plans, and select out those with good MoFEs is the next stage of the process. This allows a good and innovative plan to be formulated at the start of the campaign. As the simulation progresses, the plan is reassessed, using the same Historical Analysis algorithms. If the MoFE indicate that the plan is failing, this corresponds to a *key decision*, and a plan repair process can be put in train. A search of other neighbouring solutions which would improve the existing plan through choice of a different Course of Action takes place. More details of this whole approach to C2 can be found in Reference 5.

Implementation and Validation

At the joint campaign level, the significant new UK constructive simulation model developments based on this approach are COMAND and DIAMOND. COMAND is a C2 centred representation of the Maritime and Air campaign in a warfighting context which complements our existing model CLARION of the Land/Air campaign. DIAMOND is a high level representation of Peace Support Operations. Additional support models such as SIMBAT (a C2 centred representation of land combat at the tactical level) have also been developed to underpin these. All of these models are undergoing rigorous review and comparison with historical scenarios as part of their validation process. Since these models are based on the same coherent approach to the representation of C2, as we have described above, this process also then builds a set of validations of the C2 representation itself. A snapshot from this process is described.

Validation in COMAND

The COMAND model has been recently run under the assumptions of the Falklands War of 1982. Three main types of agent decision making were represented in this comparison:

- a). In terms of the (deliberate) campaign plan for each side’s maritime assets, this consisted of a string of missions. At various points, triggers were built into the plan, allowing it to fork to a new string of missions dependent on the situation at the trigger point (this might be the sinking or not of a major warship for example).
- b). In terms of rapid planning, maritime missions could be adapted to reflect local circumstance. For example a UK ship in transit to a patrol area could mount an attack of opportunity if its sensors detected such a threat and the attack was likely to succeed.
- c). Air missions were developed and prosecuted as a function of the sensor information on targets. For example all Argentinean air missions attacking the UK task force were created by the model in response to sensor information (mainly from Maritime Patrol Aircraft (MPA) and sensors based on the Falkland Islands).

Figure 2 shows a comparison between the actual number of UK ships destroyed, and the number predicted by the model. The dashed line shows the cumulative number of UK ships destroyed. The solid line is the simulation prediction, and 95% confidence limits.

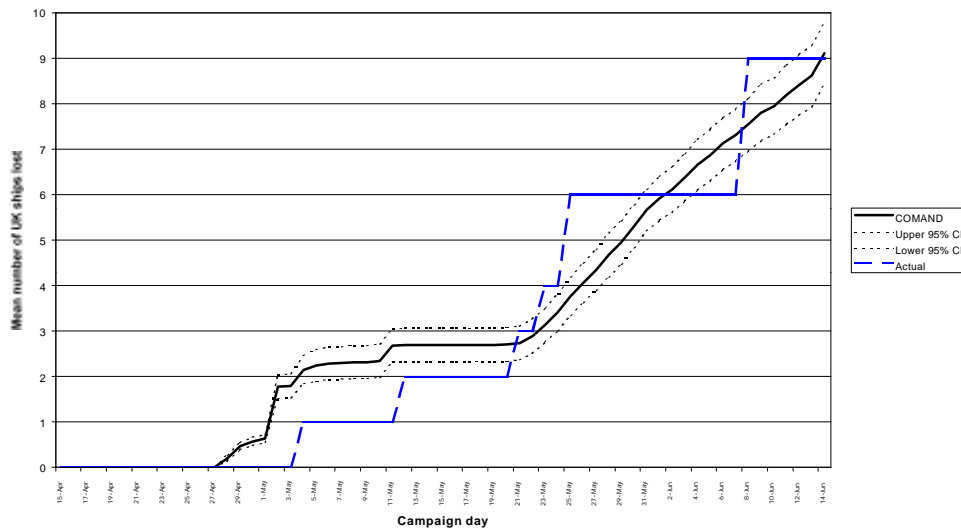


Figure 2: Cumulative Plot of UK ship losses.

If we now look at the ship groups where these occurred, we see that this is well captured by the simulation:

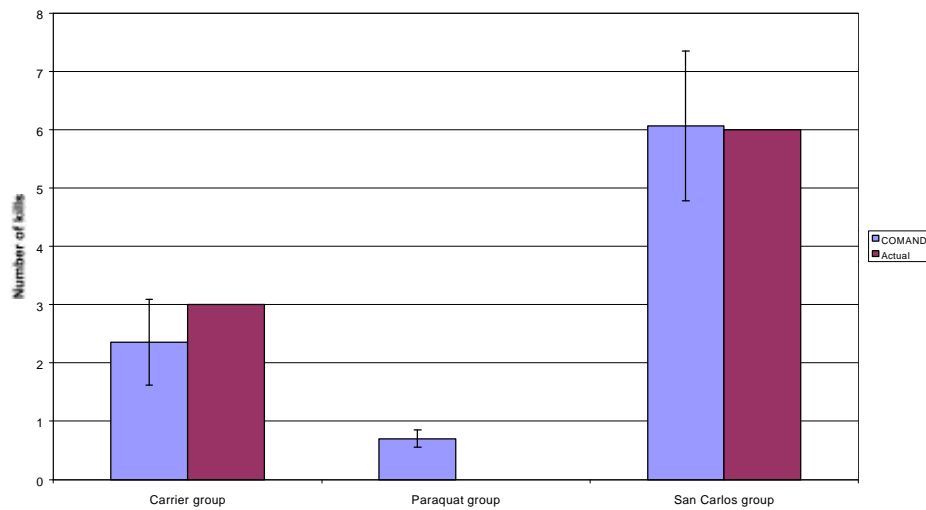


Figure 3: UK ship losses by ship group.

In each case in Figure 3, the left hand bar is the simulation prediction and confidence limits; the right hand bar is the actual result.

As a final example from this validation, consider the losses of Argentinean aircraft over the period of the war compared to the simulation prediction. Again the results are close.

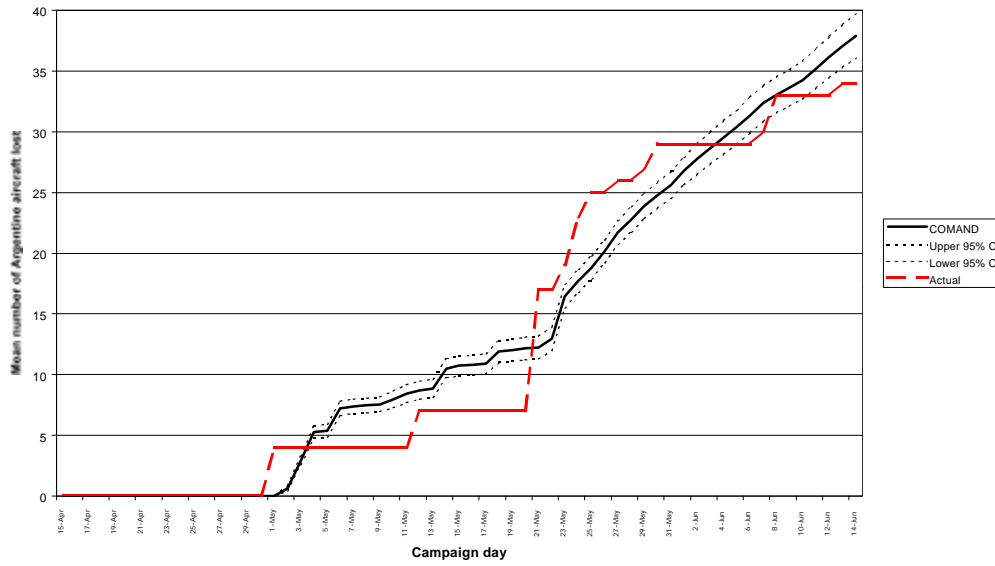


Figure 4: Losses of Argentinean Aircraft.

Mathematical modelling and metamodels

Since this new generation of simulation models is driven by the command structure and military decision making process, the behaviour of such models, is likely to be both rich and diverse. This gives a richer canvas on which analysis can be performed, and is a challenging intellectual exercise. Gaining understanding of the key drivers of the behaviour of such intelligent agent based models is thus important.

Finally then, here is an example of how such insight can be gained, using the classical scientific approach of developing a mathematically based theory of the system behaviour. I call these metamodels, since they capture higher level aspects of the behaviour represented by the constructive simulation model. More detail of this approach is contained in References 5,6.

Firstly, what evidence is there on which we can base such a model? Consider, for example, the work of Dean Hartley. In Reference 7, Hartley has analysed eight separate authoritative databases of historical combat data. These eight datasets also span several centuries in time, include both Air and Land conflicts and span the range from small to large interactions. On the basis of this extremely extensive set of data, Hartley was able to develop a stable analysis of the relationship between casualties in conflict and initial force ratio, based on earlier ideas of Helmbold. Given initial force sizes x_0, y_0 and final force sizes x, y he defines the following two dimensionless variables:

$$\text{HELMRAT} = \frac{x_0^2 - x^2}{y_0^2 - y^2}$$

$$\text{FORRAT} = \frac{x_0}{y_0}$$

Hartley has established on the basis of the comprehensive data sets examined, that (in logarithmic terms)

$$\text{Ln (HELMRAT)} = \alpha \text{Ln (FORRAT)} + \beta$$

i.e. a power law relationship, where the expected value of α is approximately 1.35 and the value of β is approximately normally distributed about the value -0.22 with standard deviation 0.7. Hartley shows that the value of α has the characteristics of a universal constant, being stable over four centuries of time, and stable when considering conflicts of different sizes, ranging from force sizes of less than 5000 to more than 100,000. Other extensive investigations show evidence of both power law and scaled distribution behaviour in real conflict data (see Reference 6 for more detail).

A Metamodel of Battlespace Control

Consider then, as shown in Figure 5, the Area of Operations (AO) of a military commander. For simplicity we assume this is a square of side L .

We assume that the commander aims to establish control in this area. Firstly we have to define what this means. Each unit, shown by a dot in Figure 5, has an area surrounding it which it can control. The size of this area is defined by the nature of the force and its associated sensors⁸. Let this area correspond to a square of side l . We assume that l is significantly smaller than the dimensions of the battlespace area of operations (the AO). Let A be the area of the AO.

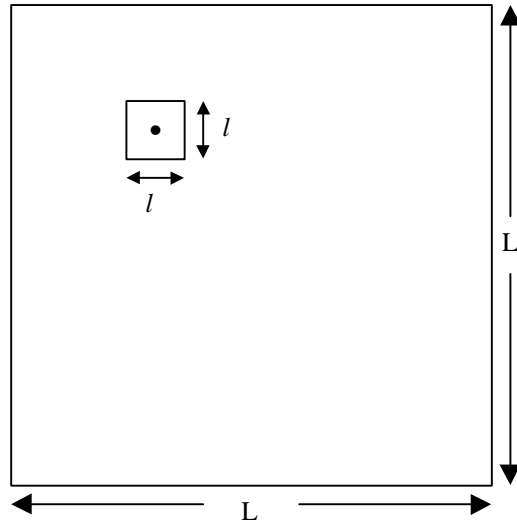


Figure 5: Area Controlled by a Single Unit.

Now let D be the fractal dimension of the force under the commander's control within the AO. (Later we will show an example of this fractal dimension as measure of local force clustering/collaboration). Suppose we partition the AO into square cells of width l . Let N be the total number of such cells, so that $Nl^2 = A$. Let $N(0)$ equal the number of cells in the AO which are occupied by one of the units making up the force. By definition of the fractal dimension, we have that $N(0) = l^{-D}$. If p is the probability that a cell chosen at random in the AO is under control, then

$$p = \frac{N(0)}{N} = \frac{l^{-D}}{N} = \frac{l^{2-D}}{A}$$

Note that D always lies between 0 and 2, so that p is well defined. For fractal sets, p is a standard measure of clustering⁹.

We define the commander to have ‘weak control’ of his area of operations if he can to some extent control movement through the AO. We define weak control as corresponding to a span of controlled areas which stretch either from side to side or top to bottom of the AO. Following on from this, we define the commander to have ‘strong control’ of the AO if there is a span of controlled areas stretching *both* from side to side *and* top to bottom of the AO, resulting in a strong constraint on the flow of people (either hostile or civilian) through the area.

The question at issue is then; how do these concepts of control relate to the ability of the force to collaborate locally (as measured by the fractal dimension)?

Consider first a cell of four elements, where each cell is a square of side l which a single unit can control. We now consider the probability p_1 of weak or strong control of this square cell of side $2l$ in terms of the probability $p = \frac{l^{2-D}}{A}$ of a unit controlling each of the squares of side l . We consider each of the five different classes of configuration for this cell, as shown in Figure 6.

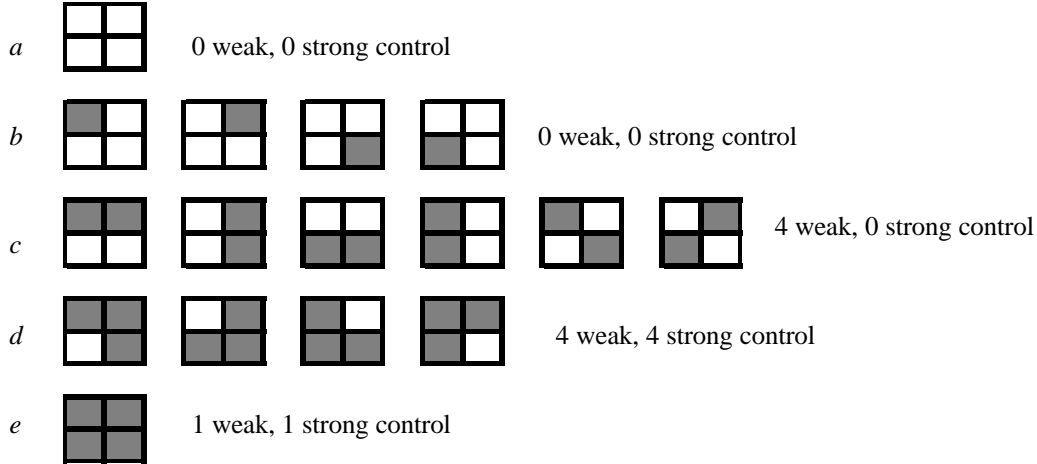


Figure 6: Configurations of the squares of side $2l$.

In Figure 6, we show the five classes a to e of configuration, and mark beside each case whether this gives weak or strong control, by considering the span of controlled areas.

The probability of each configuration can be derived in terms of p . For example the probability of any of the cases in configuration d is $p^3(1-p)$. By adding up the configurations corresponding to weak control, and taking into account the probability of each such configuration, we have the relation

$$p_1(\text{weak}) = 4p^2(1-p)^2 + 4p^3(1-p) + p^4$$

We can do the same thing for strong control, leading to the relation:

$$p_1(\text{strong}) = 4p^3(1-p) + p^4$$

Using the Renormalisation Group approach^{9,10}, we iterate at increasing levels of cell size, leading to the relations:

Weak control:

$$p_{n+1} = p_n^2(4 - 4p_n + p_n^2)$$

Strong control:

$$p_{n+1} = p_n^3(4 - 3p_n)$$

These give rise to the recursive schemes shown in Figures 7 and 8. The relations for weak and strong control above correspond to the relationships respectively:

$$f(x) = x^2(4 - 4x + x^2)$$

$$g(x) = x^3(4 - 3x)$$

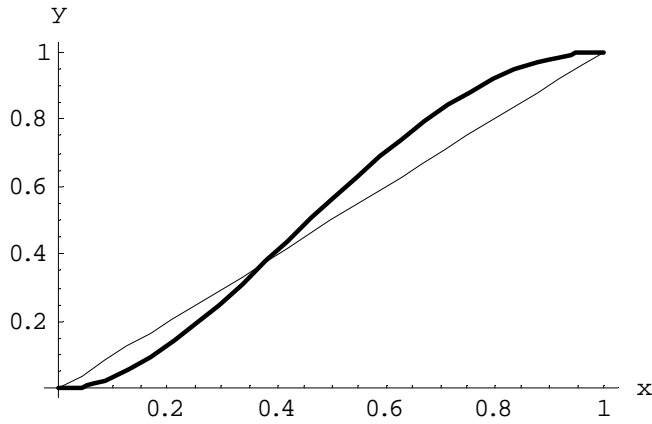


Figure 7: The recursive relation $f(x)$ for weak control.

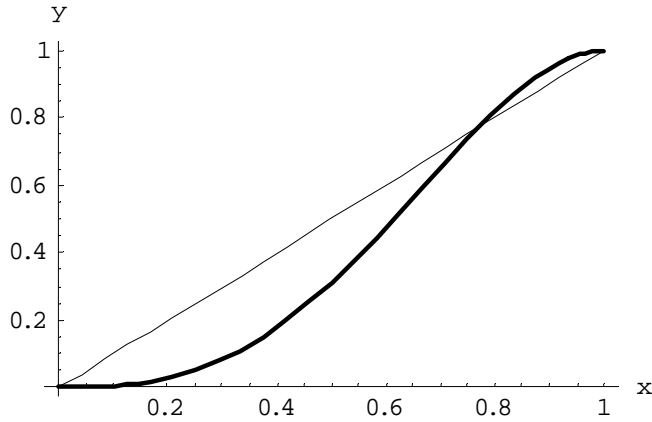


Figure 8: The recursive relation $g(x)$ for strong control.

The fixed points in the recursive relation of weak control correspond to the values x shown in Figure 7 such that $y=f(x)$ intersects $y=x$. Similarly for strong control, the fixed points correspond to the values x such that $y = g(x)$ intersects $y = x$. For both weak and strong control, there are stable fixed points at $x=0$ and $x=1$. However, there is also an unstable fixed point between these which is different for strong and weak control. For weak control, this was calculated to be 0.4 and for strong control, to be 0.8.

In either case, starting with a given fractal dimension D for the force, and the dimensions of the AO, we can calculate a corresponding starting probability $x = p_0 = \frac{l^{2-D}}{A}$. Consideration of Figures 7 and 8 indicates that there is a critical value

of the probability $p_0 = \frac{l^{2-D}}{A}$ corresponding to a critical value of fractal dimension

$D(crit)$ such that values above $D(crit)$ polarise towards very good control, whereas values below $D(crit)$ polarise towards very poor control. In the competition for control between two competing forces, we would thus expect one force to achieve rapid lock in to high levels of control, and the other to rapidly spiral down to low levels of control. Smooth change in the clustering ability of the force thus leads to an abrupt change of phase in higher level emergent force behaviour.

Using a metamodeling approach we have thus scoped the linkage between the Measure of Merit of Battlespace Control (i.e. a high level output in problem formulation terms), and the key driving variable of local force collaboration (as measured by the fractal dimension). We have shown that the probability of strong or weak control of the area of operations (AO) for a force can be determined using an iterative approach based on the renormalisation group. The fundamental emergent behaviour of such a model, in polarising to either very high or very low control of the battlespace, comes through clearly from such an analysis. This then leads us to a more refined analysis using more detailed simulation models.

It turns out that fractals, power laws and renormalisation groups are all closely connected ideas when used as the start point for a metamodel^{5,6,11}.

Fractal Dimension and Clustering in warfighting

As we have seen, the fractal dimension of a set of agents is a dimensionless measure of the ability of those agents to cluster and collaborate locally. In the context of problem formulation it helps us to investigate some fundamental dynamics and drivers in the problem. In warfighting, the ability to form local clusters allows for the creation of local force ratios which are to that force's advantage. It thus turns out^{5,12} that the attrition rate for one side in such an agent based model is correlated to the fractal dimension D of the opponent. This represents a generalisation of the Lanchester equations for attrition rate. (Such Lanchester equations only consider the gross force level, and not its clustering structure). As an example of such a fractal dimension measurement, Figure 9 shows the calculation of the fractal dimension of the "Blue" force in the HiLOCA simulation testbed (developed as part of our research) at a particular point in time using a 'box-counting' approach. The y-axis shows the number of occupied grid squares or 'boxes', and the x-axis shows the (normalised) grid interval (related to the length of the side of the box). The consistency of slope indicates a stable value of fractal dimension for the deployed force.

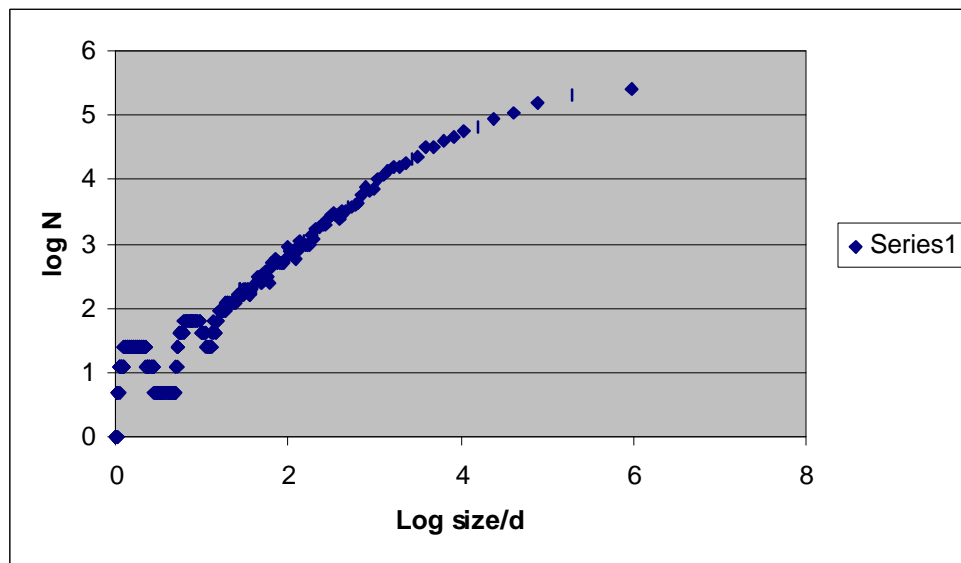


Figure 9: Calculation of fractal dimension in the HiLOCA model.

Conclusions

The uncertainties of future scenarios require us to carefully investigate the real problems and issues to be addressed in modelling and analysis of Command and Control. This problem formulation process then needs to be supported by new tools for problem solution. In consequence, a new generation of Command and Control centred constructive simulation models of conflict is being developed by Dstl in the UK. These have a coherent approach to the representation of C2 based on the ideas sketched out above. This baseline approach can then be complemented by mathematical models of such processes which give insight into the likely modes of emergent behaviour.

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